

UNITED STATES PATENT APPLICATION

of

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for

**METHODS AND APPARATUS FOR MANUFACTURING BIOELECTRONIC
DEVICES**

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RELATED APPLICATION

5 This application stems from U.S. Provisional Application Serial No. 60/138,332, filed on June 9, 1999.

BACKGROUND OF THE INVENTION

Field of the Invention

10 The present invention relates to fabrication of electronic structures involving biological or biochemical components.

Background Information

15 Electronic and electromechanical components are presently fabricated in large, industrial manufacturing facilities that are tremendously expensive to build and operate. For example, semiconductor device fabrication generally requires

specialized microlithography and chemical etching equipment, as well as extensive measures to avoid process contamination.

The fabrication processes ordinarily employed to create electronic and electromechanical components are expensive and limited in the quantities, which 5 they can produce. In addition they typically involve harsh conditions such as high temperatures and/or caustic chemicals. The ability to integrate the manufacture of such electronic and electromechanical components with biological and bioorganic molecules is becoming increasingly important. An example of this integration is the so-called "biochip," i.e., an electronically active or readable substrate 10 having a dense array of different biological materials (e.g., DNA probes). Such a chip can be used, for example, to identify samples of interest or to test for the presence of various molecular sequences. See, e.g., U.S. Patent Nos. 5,605,662, 5,874,219, and 5,837,832.

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SUMMARY OF THE INVENTION

The present invention provides an alternative to traditional fabrication of electronic components that is economical, scalable and facilitates incorporation of delicate materials. In particular, the invention utilizes nanoparticles to create, through deposition and patterning, microelectronic devices that incorporate biological materials. As used herein, the term "biological material" means any biological, bio-organic, or organic material exhibiting biological activity or capable of 20

interacting with a biologically active material; examples of biological materials include, without limitation, proteins, polypeptides (ranging from small oligopeptides to large functional molecules), nucleic acids, polysaccharides, carbohydrates, enzyme substrates, antigens, antibodies, pharmaceuticals, etc.

5 In accordance with the invention, one or more biological materials are associated, either by direct chemical bonding or by contact, with electrically active materials provided (at least initially) in the form of nanoparticles. In one aspect the invention exploits the fact that many physical, electrical, and optical properties that appear constant in the bulk of organic and inorganic materials are size-
10 dependent at the very small scales characteristic of nanoparticles. At these sizes—ranging from nearly 1 to 999 nm—the ratio of surface atoms to interior atoms becomes non-negligible, and particle properties therefore lie between those of the bulk and atomic materials. Monodisperse (i.e., uniformly sized) or polydisperse nanoparticles can form stable colloids in appropriate dispersing media, fa-
15 cilitating their deposition and processing in a liquid state. As a result printing technology can be utilized to deposit and pattern nanoparticles.

Furthermore, a key property that changes at small sizes is melting point. The effect is substantial; in some semiconductors, melting points have been ob-
10 served to drop more than 1000 °C from the bulk material. The melting point de-
pression observed in nanoparticle systems facilitates the low-temperature sin-
tering, annealing, and melting of nanoparticles into crystalline films. As a result, nanoparticles can be printed and heated at low temperatures to form films of the

bulk material, in some cases without damage to associated biological materials, or can instead be printed and left in dispersed form to retain the size-dependent properties characteristic of the nanoparticles. Alternatively nanoparticles may be printed to form electronic, microelectromechanical or microfluidic devices and 5 then subsequently biological material may be printed or added to form a bioelectronic component.

Unlike conventional electrically active particles, nanoparticles are formed not by grinding, but instead via chemical methods (such as pyrolysis) or physical methods (such as physical vapor synthesis). Nanoparticles useful in accordance 10 with the present invention may be pristine or surrounded by a “capping” group to passivate the surface, alter surface chemistry, facilitate dispersion in a liquid, or, in many applications, to bind a biological material. Following their deposition, nanoparticles can self-assemble to form highly ordered thin films and superlattices that may exhibit multiple phases.

15 Accordingly, in a preferred embodiment, the invention comprises a method of fabricating a bioelectronic component. In accordance with the method, nanoparticles are surrounded by attached shells of at least one biological material. The nanoparticles may then be deposited (e.g., using a printing process) onto a surface. By associating the deposited nanoparticles with one or more electrical 20 contacts, electrical measurement across the nanoparticles (and, consequently, across the biological material) may be made. The device may include a plurality of layers formed by nanoparticle deposition. The nanoparticles within each de-

posited layer may be immobilized (by fusing, melting, or annealing the particles into a continuous material, by curing the carrier into a permanent matrix, by surrounding the nanoparticles with bifunctional surface groups that link adjacent nanoparticles, or merely by evaporating the carrier using heat or low pressure) in 5 order to facilitate performance of the intended function. Also within the scope of the invention are components fabricated in accordance with the methods hereof.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of 10 which:

Fig. 1 is a greatly enlarged side elevation of a chemFET transistor device fabricated in accordance with the present invention;

Fig. 2 is a greatly enlarged side elevation of an alternative chem- 15 FET transistor;

Fig. 3 is a greatly enlarged depiction of a SET transistor device fabricated in accordance with the present invention; and

Fig. 4 is a greatly enlarged microfluidics device fabricated in accordance with the present invention.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

1. Nanoparticle Synthesis and Suspension

Particles useful in accordance with the present invention may be mono-disperse or polydisperse, and may represent a homogeneous suspension of a single species of nanoparticle or a heterogeneous suspension of different nanoparticles. Representative classes of nanoparticle include insulators (e.g., silicon dioxide); semiconductors (e.g., silicon or cadmium selenide); and conductors (e.g., gold or silver).

Numerous synthetic approaches, including pyrolysis of organometallic
10 precursors, arrested precipitation, precipitation in reverse micelles, and exchange
(metathesis) reactions, have been used to generate nanoparticles. See, e.g.,
Alivisatos, "Electrical Studies of Semiconductor-Nanocrystal Colloids," *MRS Bulletin*,
15 Feb. 1998, at 18-23. In principle, virtually any nanoparticle synthesis is appropriate
for the production of nanoparticles for the purposes of the present invention.
However, because nanoparticle properties depend strongly on size,
shape, crystallinity, and surface derivatization, in practice the particle synthesis is
tailored so as to control these parameters for a particular application. In general,
if the nanoparticles are not intended for bulk thick or thin film deposition—i.e.,
they will be applied and utilized in their native particulate state without subsequent
20 fusion into the bulk material—then any synthesis yielding appropriate size
control and crystallinity can be utilized.

On the other hand, if the particles are printed as a precursor to bulk thick or thin films, the synthesis should yield particles without tightly bound or heavy capping groups. Capping groups (sometimes used during synthesis to retard particle growth) can be problematic in bulk film applications if they become

5 trapped as impurities or impede crystal growth, thereby compromising film quality. Pyrolytic syntheses using pyridines and other coordinating solvents (see, e.g., Murray et al., *J. Am. Chem. Soc.* **115**:8706 (1993)), micelle-based approaches (see, e.g., Steigerwald et al., *J. Am. Chem. Soc.* **110**:3046 (1988)), and some metathetic preparations (see, e.g., Jarvis et al., *Mat. Res. Soc. Symp.* **10** *Proc.* **272**:229 (1992)) can all yield particles free of heavy organic capping groups. U.S. Application Serial No. 09/334,873, filed on June 17, 1999 and hereby incorporated by reference, discloses techniques of metathesis synthesis to form very small particles without the use of heavy capping groups.

Although in some circumstances it is possible to attach biological materials directly to a nanoparticle, attachment is more generally facilitated by surrounding the nanoparticles with an organic capping group, which envelopes the typically inorganic particle core as a shell capable of binding to biological molecules of interest. For example, silicon nanoparticles can be coated with 3-aminopropyltriethoxysilane (present, for example, as a 5% aqueous solution in

15 which the nanoparticles are dispersed). Single-stranded DNA may then be coupled to the coated nanoparticles using the well-known *N*-bromosuccinimide method (see Keller et al., *Anal. Biochem.* **170**:441 (1988)). As an alternative example, proteins may be conveniently linked to gold nanoparticles by a chemical

linkage of said gold nanoparticle to a cysteine amino acid group either naturally present in the protein or engineered to be present in the protein.

Additionally, the capping groups can act as a critical component in a device. For example, the caps (including attached biomolecules) can act as electrical insulators or sensitizers.

Nanoparticles are known to self-assemble into ordered arrays and super-lattices, both with and without capping groups. If such ordered films orient not only particles but also their crystal planes, then long-range crystal order may be expected upon sintering, annealing, or melting. Highly faceted particles may be more likely to align their crystal planes than unfaceted particles. Self-assembly also offers the possibility of printing multiple phases or layers in a single pass, or for printing some pre-assembled structures or structures that assemble during the printing. Thus, different layers or regions might form as a result of a single printing step. Layers may form by size affinity, with large and small particles tending to group with other particles of similar size. See, e.g., Heath et al., *J. Phys. Chem. B* 101:189 (1997) and Dabbousi et al., *Chem. of Mat'l's.* 6:216 (1994), showing size-based particle clustering. Three-dimensional structures have been observed to occur when particles of different sizes are brought together and small particles cluster around single large ones.

2. Applications

Nanoparticles suspended in a liquid can be deposited and patterned onto a substrate using any of a wide variety of processes, including ink jetting, spin-coating, casting, lithography, gravure printing, screen printing, impact printing, 5 stamping, embossing, contact printing (whereby a liquid or solid pattern is transferred from a plate, stamp or cylinder), or transfer onto the substrate through a mask. Moreover, nanoparticles may be applied in the dry state by dry jetting, laser printing or electrophotography (whereby a substrate receives a charge pattern and the particles are drawn to the charged regions). Deposition or application 10 may generally occur in an uncontrolled atmospheric environment, but a controlled atmosphere generally provides better process control. The deposited layers may serve as conductive, semiconductive, or insulating layers, chemically or biologically active layers, or as etch resists, light barriers, diffusion barriers, passivation layers, adhesion layers, encapsulants, or structural supports.

15 A representative application of the present invention is fabrication of chem-FETs. In a traditional field-effect transistor, the electrical resistance of the current path between source and drain elements is varied by applying a voltage to the gate element, which is separated from source and drain by a dielectric. In a chemFET, the metal gate element is removed, and the dielectric used as a 20 sensor surface. When charged species such as polar molecules or ions bind to the dielectric, the source-drain conductivity is altered, and this change can be detected and measured through operation of the device. Accordingly, by appro-

priately tailoring the transistor structure, specific chemicals or reactions may be sensed through their interaction with the transistor surface. For example, if biological material comprises single-stranded oligonucleotides, hybridization of the oligonucleotides may be detected (see Souteyrand et al., *J. Phys. Chem. B* 5 **101**:2980 (1997)). Attachment of the biological material may be by specific chemical interaction with the surface of the nanoparticle or nanoparticle-derived film. As another example an antibody may be attached to the surface of the printed chemfet enabling electronic detection of antigen binding.

As shown in FIG. 1, a chemFET 100 in accordance with the present invention comprises a semiconductor layer 110, source and drain elements 120d, 120s, and a dielectric layer 125 applied thereover. Semiconductor layer 110 may be formed by deposition of nanoparticulate CdSe, CdS, CdTe, Si, or other semiconductor onto a suitable substrate (not shown). Source and drain elements 120d, 120s may be formed from nanoparticle silver, chromium, gold, copper, 10 aluminum or other metallic dispersion. To form layer 125, a nanoparticle dispersion of silicon dioxide or barium titanate is deposited onto the coplanar surfaces of semiconductor layer 110 and source and drain elements 120d, 120s. These materials may be left as deposited, or may instead be sintered, annealed, or melted to form layers with electronic properties approaching those of the bulk 15 material. Annealing, for example, can take place during printing, after each printing step, or following deposition. As with any bulk film, annealing can consist of multiple stages of treatment at different temperatures (e.g., temperature ramp-up and/or thermal shock), heating mechanisms, durations, or ambients to im- 20

prove selected electrical and/or mechanical properties. To anneal the particles, the temperature of the environment is elevated to a point high enough to remove the capping groups (if any) and to cause fusion, annealing, or melting of particles in all layers for which a bulk film is desired. Alternatively, electromagnetic radiation, such as from a heat lamp or laser, may be used to thermally convert the 5 nanoparticles to their bulk state.

This configuration facilitates the detection of specific biological materials 130 disposed on layer 125. In the case of oligonucleotides, for example, hybridization with complementary nucleic-acid strands can be detected. Layer 125 may 10 be configured for interaction with biological material 130 in any of various ways. In one approach, layer 125 is an insulator film fabricated by sintering a deposited nanoparticle colloid and subsequently treating the material to expose reactive hydroxyl groups that bind with the biological material. In one instance such biological material may be disposed on the insulator by means of printing or micro-spotting the biological material onto the appropriate location. Alternatively they 15 may be self assembled by means of specific chemical interactions with layer 125 or electrostatically assembled by applying a potential to the device electrodes. In certain cases dielectric layer 125 may be obviated and biological material 130 attached directly to semiconducting layer 110.

20 The transistor illustrated in FIG. 1 may be connected to other printed or non-printed components to form functional electronic circuits. The means of connection may, for example, be established by deposition of nanoparticle con-

ductors and, if necessary, insulators. These circuits may be connected to other printed or non-printed electronic, mechanical, chemical, or electromechanical devices.

Alternatively, a dielectric layer can consist of unsintered nanoparticles.

5 These may either be insulating nanoparticles or beads with attached biological material. Alternatively they may be conducting or semiconducting and will collectively act as an insulator due to retention of the capping group, which thereby provides sites for chemical modification (so that the biological material reacts with the cap, or a material subsequently bound to the cap, rather than with the

10 inorganic nanoparticle material). Referring to Figure 2, a chemFET 200 comprises a semiconductor layer 210, a source element 215s, and a drain element 215d. These constituents may be fabricated as discussed above, i.e., by deposition and sintering of nanoparticles having appropriate conductivities. A layer 220 of nanoparticles having a biological material of interest attached thereto is applied onto semiconductor layer 210 between source and drain elements 215d, 15 215s. Such nanoparticles with attached biological material would generally be insulating nanoparticles or beads with directly bound biological material. Alternatively they could be conducting or semiconducting nanoparticles with appropriate capping groups. Such biological material may be positioned appropriately in one 20 instance by means of printing or microspotting the biological material. Alternatively said biological material be self assembled by means of specific chemical interaction or electrostatically assembled by applying a potential to the device electrodes.

In one exemplary embodiment, monoclonal antibodies are attached to nanoparticles 220 in the manner presently used to attach them to latex beads and other stationary supports. The various fractions of an electrophoretic protein separation are passed over the layer 220, and when a binding fraction is 5 reached, the binding reaction is revealed by the change in measured electrical current from source to drain. In another embodiment, nucleic-acid probes are attached to nanoparticles 220, and candidate nucleic-acid fragments are passed over the layer 220. When a complementary fragment hybridizes with the bound probes, this is once again revealed by the change in measured electrical current 10 from source to drain.

Referring to the preceding description of device 200, an alternative configuration is one in which layer 220 is obviated and biological material is instead bound directly to conducting or semiconducting nanoparticles which are then further disposed, unsintered, between electrodes 215d and 215s. The same 15 types of biological materials, the same ways to dispose them in the appropriate location and similar electrical readout means obtain.

Subj FIG. 3 illustrates formation of a single-electron transistor (SET). Like chem-FETs, SETs can detect the absorption of charged material. The advantages of SETs are, first, that the gate is on the length scale of single molecules, 20 and second, that the charge sensitivity is several orders of magnitude greater. In accordance with this approach, illustrated in FIG. 3, a SET 300 is self-assembled by binding a single nanoparticle 310 between two conducting contacts 315, 317.

The contacts may, for example, be synthesized carbon nanotubes with modified chemical ends such that the nanoparticle self assembles onto them. Alternatively electrodes may be formed by printing conductive nanoparticles or by conventional photolithographic or other means and then employing electromigration, 5 electroplating or electrofusing under feedback control to realize the nanoscale electrode spacing required for single electron transistor operation. Thus formed, contacts 315, 317 are exposed to a solution of nanoparticles having capping groups and, radiating therefrom (typically as a tangle of minute threads), biomolecules of interest. The interelectrode spacing distance approximates the size 10 of the nanoparticles, so that a single nanoparticle can lodge between the electrodes and bridge them. Reagents affecting the biological material may be directly adsorbed onto (or absorbed into) the nanoparticle, and the effect monitored by operation of the device.

As described, a SET typically consists of a single nanoparticle disposed 15 between two nanoelectrodes and insulated from those nanoelectrodes by means of insulating capping groups. An alternative arrangement consists of a chain of nanoparticles between electrodes insulated from each other and from the electrodes by means of insulating capping groups. Such a chain may be formed by applying an electric field to the electrodes in the presence of a solution of nanoparticles. Conduction is by means of electron hopping. If the nanoparticles have 20 associated with them biological material, then the hopping probability and thus the current flow is affected by other molecules interacting with the associated biological material and may be measured.

In addition to chemFETs and SETs, electrometers for sensing charged material can also be fabricated using a technology known as light-addressable potentiometer systems (LAPs) or single point potential (SPP) electrometers. The principle is nearly identical to that underlying chemFETs except that only one 5 electrode per device is required. These devices, too, can be printed with nanoparticle technology.

For biochips, many reactions are analyzed in parallel, requiring arrays of integrated sensors. Devices such as chemFETs, SETs, or SPPs can be printed in arrays where rows and columns are isolated from each other (as described, for 10 example, in copending application Serial No. 08/820,057, filed on March 18, 1997 and entitled PRINTABLE ELECTRONIC DISPLAY). A memory circuit can also be constructed using printed SETs in accordance with copending application Serial No. 09/291,801, filed on April 14, 1999 and entitled MEMORY 15 STRUCTURES AND METHODS OF MAKING SAME. The entire disclosures of both of these applications are hereby incorporated by reference.

In another application of SET technology, a polymerase molecule (generally bound to a nanoparticle) is suspended between SET electrodes. Nucleic-acid polymerases are enzymes that catalyze synthesis of a nucleic-acid chain based on a template. In the presence of appropriate nucleosides, a polymerase 20 follows the template (which may be single- or double-stranded DNA, or RNA) and causes synthesis of its complement. In accordance with one aspect of the present invention, the applied field is used to sense the conformational change of the

enzyme during synthesis, thereby revealing the sequence of the template strand (as well as the synthesized strand). That is, the electrical signal produced by the SET during the course of synthesis encodes the identity of the template and synthesized strands, since the conformational changes—and the corresponding 5 effects on current flow through the SET—of the polymerase are characteristic for particular bases.

In a related aspect, the synthetic action of the polymerase is directed rather than merely observed. The polymerase enzyme functions by means of a catalytic reaction crevice whose conformational attributes are altered slightly by 10 interaction with a nucleotide base from the template. Using one or more nano-electrode or STM tips applied to the polymerase, the molecule can be caused to selectively assume conformational changes, which will induce 'errors' in the copy of a homopolymer template. Such 'errors' may encode data either as memory or to be fed into another polymerase attached to a SET readout. Such a system 15 thus realizes the basic components of a read and write memory system.

Figure 4 illustrates an electrically controllable microfluidic. In this case, a linear drive motor 400, which is useful for transporting biological molecules which may be bound to nanoparticles or beads 430 for the purpose of carrying out chemistry and transport. The device is created by printing conducting nanoparticles to form the three phases 401, 402 and 403 of three phase linear drive motor. 20 In addition walls or fluidic channels may be printed for containment of a fluid media.

Although the present invention has been described with reference to specific details, it is not intended that such details should be regarded as limitations upon the scope of the invention, except as and to the extent that they are included in the accompanying claims.

5 What is claimed is:

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